

Weight and the Future of Space Flight Hardware Cost Modeling

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Abstract

Weight has been used as the primary input variable for cost estimating almost as long as there have been parametric cost models. While there are good reasons for using weight, serious limitations exist. These limitations have been addressed by multi-variable equations and trend analysis in models such as NAFCOM, PRICE, and SEER; however, these models have not been able to address the significant time lags that can occur between the development of similar space flight hardware systems. These time lags make the cost analyst's job difficult because insufficient data exists to perform trend analysis, and the current set of parametric models are not well suited to accommodating process improvements in space flight hardware design, development, build and test. As a result, people of good faith can have serious disagreement over the cost for new systems.

To address these shortcomings, new cost modeling approaches are needed. The most promising approach is process based (sometimes called activity) costing. Developing process based models will require a detailed understanding of the functions required to produce space flight hardware combined with innovative approaches to estimating the necessary resources. Particularly challenging will be the lack of data at the process level. One method for developing a model is to combine notional algorithms with a discrete event simulation and model changes to the total cost as perturbations to the program are introduced. Despite these challenges, the potential benefits are such that efforts should be focused on developing process based cost models.

Introduction

Does weight have a future as an input variable in NASA cost estimating relationships? Recent concerns raised by NASA managers might lead one to believe that weight based parametric models are as outmoded as a Model T on the Washington Beltway. An experienced cost analyst may be tempted to dismiss such comments as evidence of a lack of understanding of our models and data bases, or as the griping of one whose project has been affected by an estimate that is higher than one believes to be the case. But should we be so smug as to suggest that the fault lies totally outside of our fine profession? Perhaps we should take the time to try to hear the truth behind the complaints. Perhaps we should examine our methods and data to see if they are capable of addressing the shortcomings highlighted by our critics. Perhaps we should explore the development of new cost models that would enable all the stakeholders of a cost estimate to come to a consensus based on the true cost drivers.

The purpose of this paper is to perform such an examination of our models and methods in light of recent criticisms. The paper begins by examining our current

parametric models and databases to determine if the issues raised by management are supported by the facts. Of particular interest is the value that weight brings to a cost model. Once the examination is complete, a new method is proposed that can bridge the gap between the cost estimator and management: process based cost models. Finally, a simplified development approach is outlined for process based cost models that can overcome the limitations in data.

Weight and Cost Estimating

Why is weight (or board count, or volume, or some other measure of size) almost universally used as a cost model input for aerospace cost models? The answer is very simple: it is available and it works. Some of NASA's earliest cost models used weight as the key input parameter. One of the reasons weight was attractive was that it was known for both historical data points and new concepts under consideration. The other, and more important reason, is that all things being equal, there is a consistent correlation between size and cost. This relationship is demonstrated in Exhibit 1 by plotting the total cost development cost of all NAFCOM space vehicles (satellites, human rated vehicles, and upper stages) against weight.

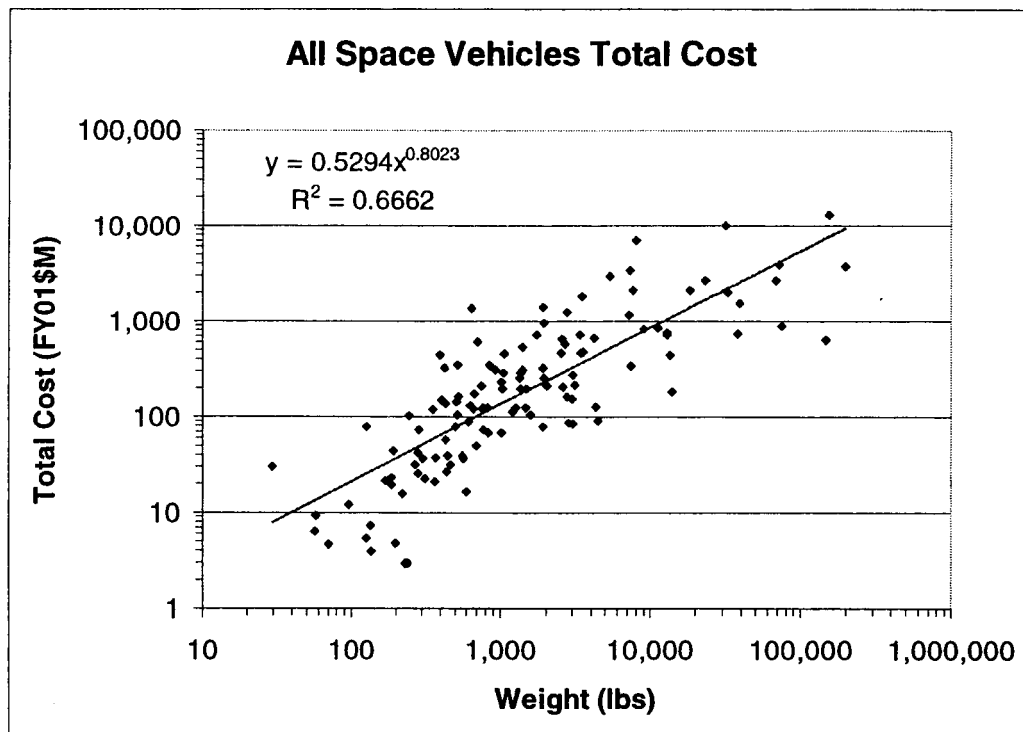


Exhibit 1. Relationship between Weight and Cost of Space Vehicles.

An important point often lost is that weight is a cost predictor, not a cost driver. Exhibit 1 illustrates this point. Notice the relatively low R^2 value and the large absolute

variance in the data. For example, a 1000 pound space vehicle could cost anywhere between \$100M and \$1000M. Obviously, not all cost drivers are being addressed.

The traditional approach within NASA to dealing with the variance problem was to segment the database into like systems and subsystems. However, experience shows that this segmentation introduces problems with the statistical analysis of small data sets and, while it reduces the magnitude of variance in the model, it does not reduce the relative variance. This is illustrated in Exhibit 2, spacecraft structures total cost and weight. The bottom line is that while weight can get us in the ballpark, it doesn't tell us what seat we are in.

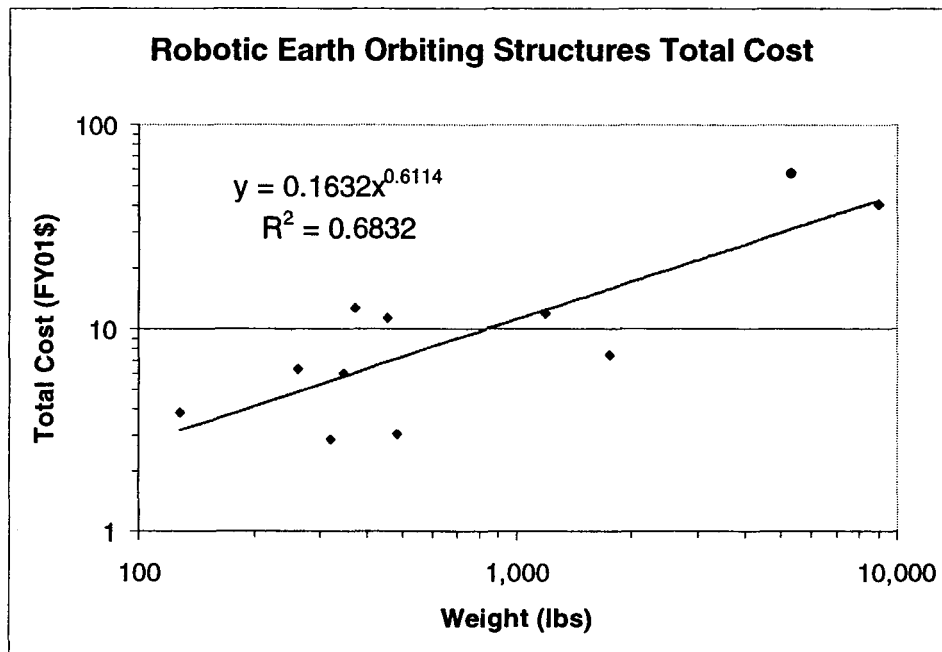


Exhibit 2. Spacecraft Structures Total Cost – Weight Relationship.

Identification and Application of the Real Cost Drivers

Weight is a great scaling parameter. Bigger things cost more, and when everything is equal, historical data points can be used in combination with the appropriate scaling relationship to estimate the cost of the new system. However, weight (or any other size parameter) cannot totally explain the cost. In fact, many factors go into determining the true cost of space flight hardware systems. Some of these cost drivers are listed in Exhibit 3.

System Design	Management Approach
Purpose	Organization of Program
Function	New versus Existing Design
Technology	Quality of Personnel
Relative Complexity	Quality of Management
etc.	Test Philosophy
	Performing Organization
	International Participation
	etc.

Exhibit 3. Cost Drivers.

These factors are well recognized by the experienced cost analyst and have been captured in various ways by numerous cost models. For example, the NAFCOM model uses system design parameters such as output power, design life, storage capacity, and power regulation to account for electrical power system design factors. NAFCOM also provides input parameters to reflect the management approach drivers identified in Exhibit 3. These include manufacturing methods, engineering management, new design, risk management, funding availability, integration complexity, and pre-development study. When these parameters are correct, the results can be quite impressive, as shown in Exhibit 4.

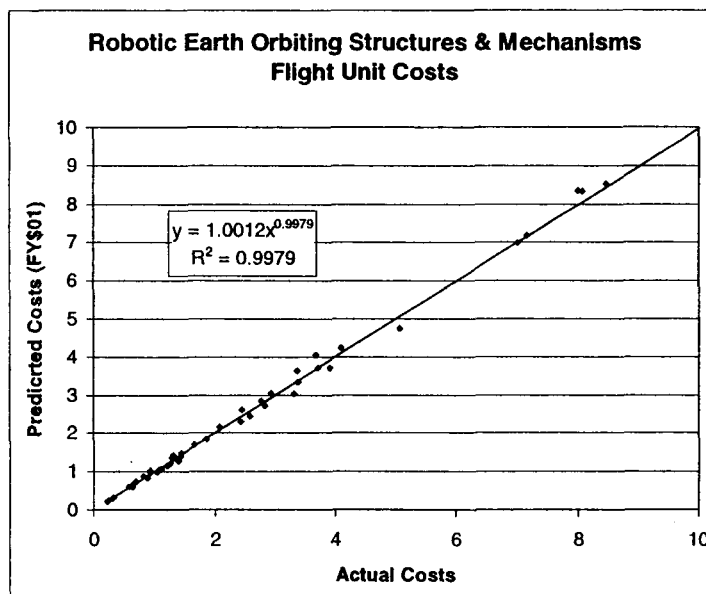


Exhibit 4. Example Relationship between Predicted to Actual Cost in NAFCOM.

Exhibit 4 shows that when a conscientious effort is made to incorporate the true drivers of cost into a model, accurate cost models are the result. Given such evidence, it would appear that NAFCOM (and PRICE and SEER) have solved all of our estimating problems. Unfortunately, the critics of parametric cost models have some legitimate complaints. These are:

- Predicts the past better than the future
- Limited support for technical design trades
- Limited support for management and process trades
- Small, imperfectly understood data sets

The latter complaint is especially relevant to the problem of accurately estimating the cost of new, reusable launch systems. Since there is only one analogous data point, the Space Shuttle, trend analysis is impossible. Technical, management, and process trades are also difficult to perform with only a single, historical data point. In the case of the RLV, the single data point problem is compounded by the age of the data point (the Shuttle was developed in the 1970's). The result is a situation where the credibility of the estimate can be questioned.

A Closer Examination of the Problem

The heart of any cost estimate is the supporting data. Plentiful and recent data that is applicable to the concept being estimated increases the confidence of both the analyst and the program manager in the cost. However, when data is neither plentiful nor recent, disagreements can arise over the interpretation of the data and its applicability to the concept under study. This concept is vividly illustrated by Exhibits 5 and 6.

Exhibit 5 demonstrates the kind of analysis that can be performed when sufficient data is available. In this case, a large database of historical small satellite missions has enabled The Aerospace Corporation to develop a mission complexity factor. This complexity factor can be plotted against cost. By identifying successful missions, a trend line can be developed which can be used to determine the likelihood of success or failure. Such an analysis, which is based on recent, relevant data, is useful to both cost estimators and program managers.

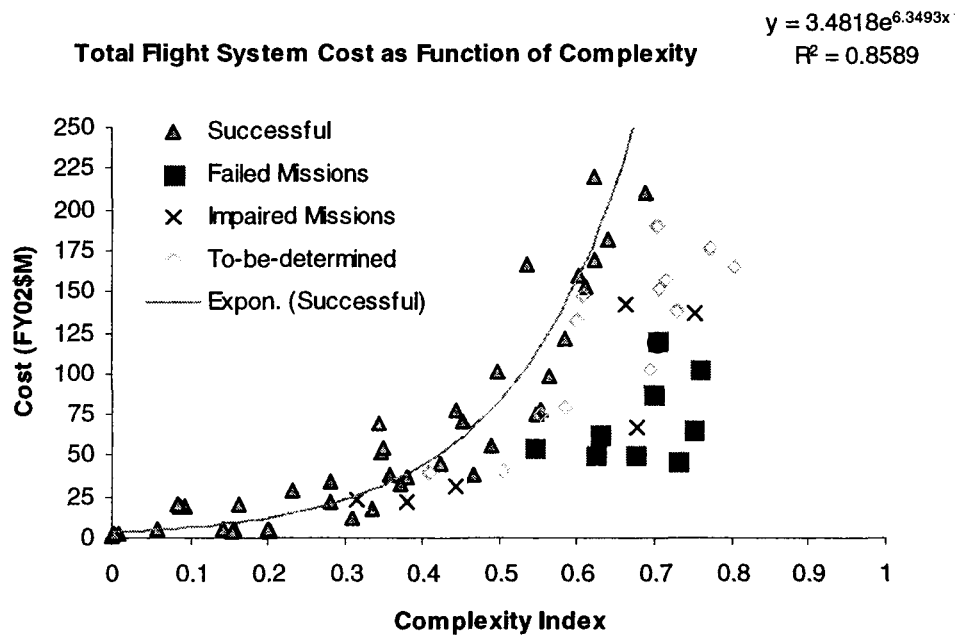


Exhibit 5. Aerospace Corporation Mission Complexity Factor.

Compare the example in Exhibit 5 with Exhibit 6. Exhibit 6 provides an example of the issues faced when estimating the cost when the supporting data set is sparse and old.

Shuttle	RLV
Solid and Liquid Rocket Engines	All Liquid Rocket Engines
Partially Reusable	Fully Reusable
Deliver Crew and Cargo to Orbit	Deliver Crew and Cargo to Orbit
Perform On-Orbit Assembly	???
Perform Satellite Servicing	???
Limited Abort Modes	Full Abort Modes
Technology Development on Critical Path	TRL 6
~ 1972 Technology	~ 2006 Technology
Apollo/Saturn V Experience	Shuttle Operations Experience
Mainframes and Slidrules	PC's, Workstations, Sophisticated Software
Development Cost Constraints	Operations/Development Cost Trades
etc.	etc.

Exhibit 6. Comparison of Shuttle and RLV Development Paradigms.

The Space Shuttle was developed almost 30 years ago. Since then technologies, design software, computer capabilities, and requirements have evolved. In addition, new processes in the management of large, high technology programs have been developed that may or may not have an impact on the development of the next generation reusable launch vehicle.

This time lag between the development and production of the only relevant historical data point and the new system can be called a temporal/cultural/technology gap. The lack of real data to fill in the gap means that the knowledge base used to adjust the parametric estimate is theoretical. It also means that consensus will be difficult to reach for program managers and cost estimators. The uncertainty engendered in NASA management over this very issue and the resulting wide range of cost estimates was one of the key factors in the decision to refocus the Space Launch Initiative program away from a replacement for the Shuttle and towards the development of an orbital space plane (OSP).

The Next Generation of Cost Models

Given that the temporal/cultural/technology gap exists, what can be done? Since the gap is caused by a limited data set, traditional methods such as adding more technical or programmatic input variables are not feasible. Other methods must be pursued. These methods must be able to address issues such as improvements in computer technology, advancements in design methods, and changes in manufacturing processes. These methods must enable the transfer of applicable experience from programs of similar scale and purpose. These methods should anticipate the questions and explain why the estimated cost is realistic.

Process based cost models may be the best approach for a tool to bridge the temporal/cultural/technology gap. Process based cost models translate spaceflight hardware system characteristics into a set of discrete activities. These activities represent processes that must be performed to develop and produce the hardware. A typical process flow for developing a spacecraft avionics subsystem is shown in Exhibit 7.

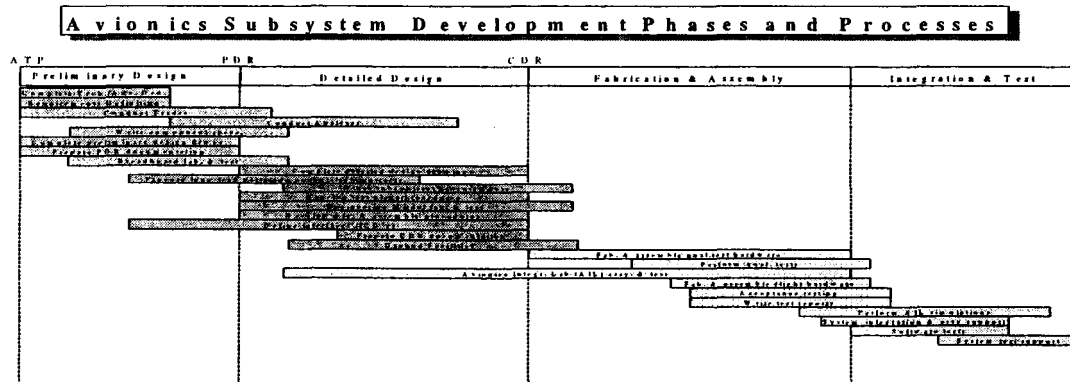


Exhibit 7. Example Process Flow.

There are several advantages to process cost model. Among these are:

- Relate cost to work performed
- Direct linkage to schedule
- Ability to tie cost to specific functions or activities (like tests)
- Identification of causal relationships between the cost, schedule, and engineering and management decisions
- Enhance communications between Project Managers, Cost Professionals and Technical Disciplines (explain Why, not just How Much)
- Anticipate cost impacts of design, development, and manufacturing trends
- Provide engineering cost support beyond early formulation

These advantages directly address the temporal/cultural/technology gap issues. By focusing on the relationship between the process and the product, how the system is being developed can be directly estimated.

The potential for revolutionizing the cost analysis profession is enormous. Process cost estimating combined with discrete event simulation will enable realistic simulations of an entire program life cycle. Management decisions can be tested for affects on cost and schedule while the program is still in the formulation phase. Development assumptions can be tested for robustness. Engineers can see how performance characteristics affect O&S cost. Cost estimates can be easily justified and understood because the results can be traced directly to the work performed.

Development of a Process Based Model for OSP

Development of a process-based model for the OSP program is a doable but challenging task. The best analog for developing the model is the Space Shuttle Orbiter. The processes followed in developing and producing the orbiter and their duration are known. Significant documentation exists and experienced aerospace engineers can provide a wealth of first hand information.

The difficulty in the development of a process based cost model for the OSP program will lie in determining the labor hours of the processes. Labor hours are used instead of cost to provide a more accurate reflection of the work performed. Existing orbiter labor hours documented by work breakdown structure (WBS) element, not by process. Reanalyzing the historical labor hour data to fit a process paradigm will require innovative and defensible approaches to allocate WBS labor hour data to the processes. Once the notional labor hour allocation is performed, the next step will be to determine the proper inputs for estimating the labor hours and schedule duration of each process.

To determine the proper inputs and responses of the model, heavy use must be made of expert opinion. Discussions will be held with subsystem design engineers, supervising engineers, system engineers, and program managers to uncover the inputs that drive labor hours and schedule duration. Expert opinion will also be used to develop notional relationships between the inputs and the changes in labor hours and schedule.

The best approach to testing the notional process model may be to use discrete event simulation to calculate the probable outcome given a set of input data. The

methodology for developing a subsystem process simulation would rely on the following information:

- Subsystem level labor hours
- Shuttle Orbiter program documentation
- Basic notional process flow model
- Discrete event simulation of the process flow

Once these four items are in hand, the discrete event simulation can be calibrated against actual orbiter program experience. The calibration exercise will follow the four-step process outlined below:

- Adjust the simulation to reflect the orbiter program as envisioned at authority to proceed (schedule, labor phasing, etc.).
- Modify the simulation to reflect challenges faced by the orbiter program, such as funding shortfalls, technical failures, and requirements changes.
- Calibrate the simulation to yield the same labor hours and schedule changes that resulted from the orbiter program challenges.
- Document the changes made to the simulation.

The use of discrete event simulation will enable the uncertainty in the notional labor hour allocations and models to be bounded. If the model gives reasonable results that agree with historical experience, the determination can be made that the model is adequate. The model can now be used to estimate the effects of improved management, engineering, and manufacturing processes. Credibility in these estimates can be established by capturing the experience from relevant programs into the model and using the model to verify the results. The model will also provide the template for how the OSP program must be managed for cost savings due to improved process can be realized.

Conclusion

The development of a process based cost model is a daunting challenge. However, if our profession is to move beyond estimating the hardware system to estimating how the system is developed, this challenge must be faced and overcome. Project managers, designers, and manufacturing engineers are constantly seeking ways to do things better. The cost analysis community must step up support these professionals by providing the cost impacts of their attempts to find better and more cost effective solutions to developing spaceflight hardware.

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